Snowmass 2021 - Letter of Interest: Magnetic Microcalorimeters for CEνNS Detection

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Low-temperature magnetic microcalorimeters (MMCs) coupled to single-crystal absorbers are a promising new approach for the detection of reactor neutrinos via coherent elastic neutrino-nucleus scattering (CEνNS). The greater bandwidth of MMC compared to other microcalorimeter technologies should allow such detectors to simultaneously achieve both low energy threshold and active background rejection. The detector concept and anticipated physics applications are described.

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
□ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
■ (NF7) Applications
□ (NF8) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors

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I. INTRODUCTION

Coherent elastic neutrino-nucleus scattering (CEνNS) is receiving increased interest for nuclear reactor monitoring and nuclear non-proliferation because CEνNS offers a larger cross section than the inverse beta decay process and does not have a reaction threshold. Achieving the best performance with CEνNS requires low-Z detector materials to maximize recoil energy, large detector mass, low energy threshold ($E < 1$ keV, as low as possible) for increased signal rate, and a low background level to minimize statistical fluctuations in the signal region.

Simultaneously realizing both low energy threshold and low background level is challenging. Semiconductor and scintillator-based detectors provide low background levels with large mass scales; however, nuclear quenching can limit their energy thresholds and increase uncertainties. Microcalorimeters are potentially an important alternative for CEνNS as they are not subject to nuclear quenching and exhibit excellent energy resolution and low energy threshold. Among microcalorimeter technologies, magnetic microcalorimeters (MMCs) are promising candidates as they are faster than than the transition edge sensors or Si/Ge thermistors. This speed enables precise pulse-shape discrimination (PSD) [1, 2] and therefore should provide the best active background rejection. Simulations indicate that MMCs are capable of achieving energy threshold of $\mathcal{O}$(10 eV) and active background rejection at E>100 eV simultaneously (Fig. 1).

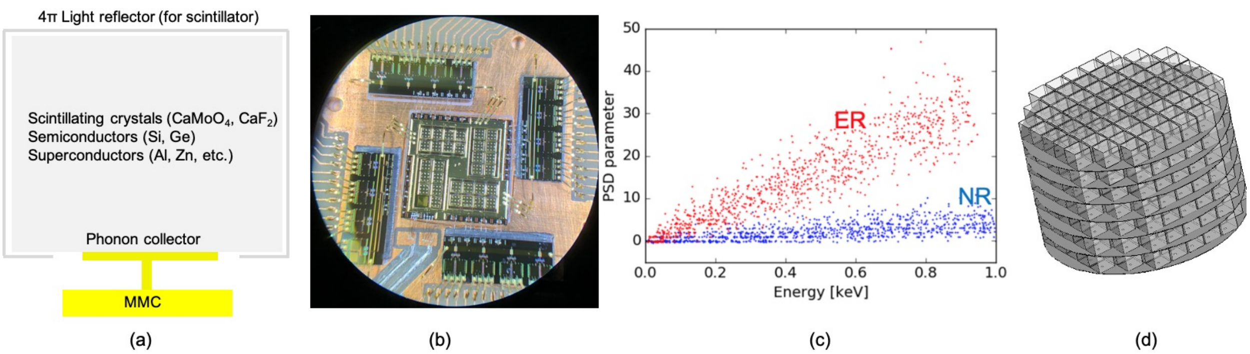

FIG. 1. **(a)** Schematic drawing of a proposed MMC-based detector **(b)** 32-pixel MMC array developed for gamma-ray spectroscopy [3] **(c)** A simulated scatter plot showing particle discrimination using PSD. Electron recoils (ER) and nuclear recoils (NR) are separated. **(d)** An example of MMC-based detector array for CEνNS detection. Each 4 inch Si wafer contains 69 MMCs and crystal absorbers.

II. DETECTOR CONCEPT

The proposed CEνNS detector consists of a close-packed array of MMC detectors, as shown in Fig. 1. Each MMC detector has a single-crystal absorber coupled to its magnetic sensor [2]. Because MMCs offer great flexibility as to absorber type and size [4], single crystals of dielectric, semiconducting, or superconducting material with size ranging from 1 cm^3 to 10 cm^3 can be used. CEνNS events in the crystal produce high-energy phonons. These phonons are collected by a Au film coated onto the crystal and then rapidly thermalize with the electrons in the film. This temperature change is communicated to the spins of the magnetic sensor through optimized Au connections. The resulting change in the sensor's near-Curie-Law magnetization is read out by superconducting quantum inteference devices (SQUIDs) as voltage output. Typical response time of this MMC configuration is $\mathcal{O}$(1 μs) [5, 6], which is faster than other microcalorimeters. The main challenge is designing the detector in such a way that the phonon collection time is fast enough to not slow down the signal, while keeping the crystal mass large and energy threshold low [7].

- **Low energy threshold.** Generally, the size of the microcalorimeter determines energy resolution and threshold. Small microcalorimeters are employed for x-ray spectroscopy that requires the best possible energy resolution. Gamma-ray and alpha spectroscopy require larger microcalorimeters to increase detection efficiency, which sacrifices some of the energy resolution. The proposed MMC-based detectors require fast phonon collection and thus large phonon collectors and MMCs. The MMCs that have been developed for gamma-ray spectroscopy [3, 5, 6] are suitable for CEνNS detection as they use large Au absorbers that can be used for phonon collection. These MMCs exhibit energy resolution of $\mathcal{O}(10\text{ eV})$, and the energy threshold is expected to be of similar order. Note that lower energy threshold can be achieved with smaller microcalorimeters; however, this would increase the phonon collection time.

- **Pulse shape discrimination.** Particle interactions in absorber crystals produce prompt phonons but also excite electrons over the band gap. Recombination of excited electrons produces delayed phonons. Recombination timescale varies by crystal type. Because the energy fractions of electron excitation vary by interaction types (electron and nuclear recoils), fractions of delayed phonons also vary. This results in different average phonon collection times and thus pulse shapes, which enables PSD for particle identification [1, 2]. MMCs are advantageous for PSD as they are faster than other microcalorimeters and can thus better resolve the delayed phonons. A detector simulation using a 1 cm^3 $CaMoO_4$ scintillating crystal and the MMCs in [5] showed that PSD successfully discriminates interaction types down to the 100 eV region 1. At such low energy region, PSD performance is limited by Poisson statistics of excitations.
- **Detector array and mass scale.** Single crystal mass will range from 1 g to 100 g. For efficient CEνNS detection of reactor neutrinos with $\sim$100 eV threshold, we aim to have a total detector mass greater than 1 kg. One example of using 1 cm^3 crystals is shown in Fig. 1. This will utilize 69 MMCs on a 4 inch Si wafer, and 69 crystal absorbers will be mounted on each MMC. These wafers will be stacked as shown in Fig. 1. The number of readouts will be reduced to 3 RF channels per wafer by using the microwave multiplexing technique. SQUIDs and resonator circuits will be all integrated on the 4 inch wafer.

III. PHYSICS POTENTIAL

MMCs' low threshold and unquenched measurement of nuclear recoils allow for study of neutrinos below the IBD kinematic cut-off such as measuring the low-energy reactor spectrum and comparing it to reactor simulations. The fast rise time of MMCs ($\sim$ μs) compared to other cryogenic detectors allows for experiments at accelerator-based neutrino sources such as the Oak Ridge National Laboratory's Spallation Neutron Source searching for neutrino magnetic moment, non-standard interactions, and sterile neutrinos [8]. A 1 kg array with sufficient shielding would produce better limits than other CEνNS experiments due to lower threshold and unquenched signal. Uncertainty in the quenching factor is dominant in other experiments and can easily result in misinterpreted physics results [9].

IV. NUCLEAR SECURITY APPLICATIONS

In the context of nuclear security such as tracking plutonium production in nuclear reactors [10] it has been argued that CEνNS could provide benefits by virtue of its greater cross section in comparison to inverse beta decay, thereby reducing the detector size. However, the benefit of cross section may not be as pronounced as usually thought when casting it in terms of mass advantage [11]. Still, the absence of kinematic threshold for CEνNS opens the possibility for detecting lower-energy antineutrinos, which may enable or enhance additional attractive applications related to the nuclear fuel cycle, such as monitoring spent fuel over long time periods [12] and detection of breeding blankets in nuclear reactors [13]. These are admittedly long-range goals that could be supported by MMC detectors scaled to sufficiently large masses, but they still highlight the potential uniqueness of the application reach that this technology offers.

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